Radiofrequency and Microwave Dielectric Properties of Shelled Field Corn

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CONTENTS

ILLUSTRATIONS

TABLES

Radiofrequency and Microwave Dielectric Properties of Shelled Field Corn

By Stuart O. Nelson[1]

ABSTRACT

The dielectric properties of shelled field corn were measured at frequencies of 20 and 300 MHz and 2.45 GHz for moisture contents between 35 and 10 percent, wet basis. Methods of measurement and sample-holder construction are described briefly. Data are presented for the values of the dielectric constant, dielectric loss factor, loss tangent, and conductivity, as a function of moisture content. Relationships between the dielectric constant and the bulk density and temperature of the corn are also illustrated. The dielectric constant exhibited less variability among corn lots than did the other dielectric properties, and it was also more consistent for repeated measurements on the same corn lot. Therefore, the dielectric constant is the most reliable of the dielectric properties to use as an indicator for measurement of moisture content. Variation in the dielectric constant among different corn lots was about the same at all three frequencies. For accurate moisture determination by electrical measurements that depend upon the dielectric properties of the grain, corrections must be made for variations in bulk density and temperature. KEYWORDS: corn (*Zea mays*), dielectric constant, dielectric loss factor, dielectric properties, electrical conductivity, grain, microwave dielectric properties, radiofrequency dielectric properties.

INTRODUCTION

The electrical properties of grain have long been used for rapidly estimating grain moisture content (Nelson 1977). Because of the need for rapid methods of moisture measurement in the grain trade, electrical instruments have been developed that measure grain moisture content with a fair degree of reliability when the moisture content is below about 20 to 25 percent, wet basis. Such instruments are used almost universally in the United States for determining moisture content in the grain trade.

Development and practices in grain harvesting and drying over the past several years have resulted in the sale of grain, particularly corn and grain sorghum, at moisture levels above the range within which presently used electrical moisture meters are reliable. Because grades and prices depend upon the moisture content of grain, inaccurate measurement of moisture content causes inequities in the buying and selling of high-moisture grain. Consequently, instruments must be developed to provide consistent and reliable results on high-moisture grain.

The better present-day moisture meters use the correlation between grain moisture content and the dielectric properties of the grain. The dielectric properties of usual interest are the dielectric constant, ϵ_r', and the dielectric loss factor, ϵ_r'', respectively, the real and imaginary components of the complex relative permittivity, $\epsilon^* = \epsilon_r' - j\epsilon_r''$; the loss tangent, $\tan\,\delta = \epsilon_r''/\epsilon_r'$; and the conductivity, $\sigma = \omega\epsilon_0\epsilon_r'' = 0.556 f\epsilon_r''$ μmho·cm^{-1}, when frequency,

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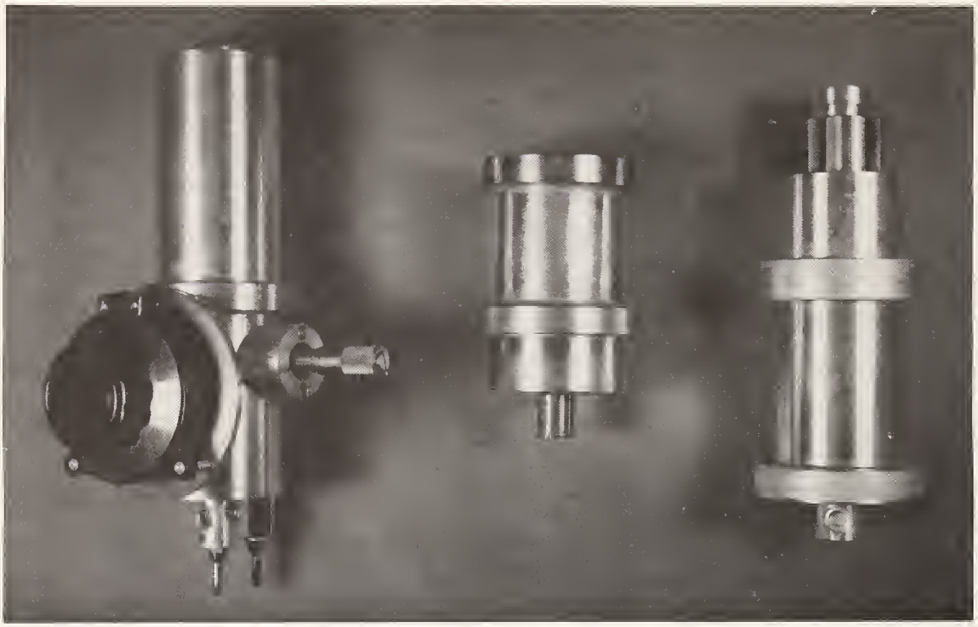


FIGURE 1.—Coaxial-line sample holders for corn measurements. Left to right: sample holder for use with Q-meter at 20 MHz; sample holder for use with admittance meter at 300 MHz; sample holder for use with Rohde and Schwarz nonslotted line at 2.45 GHz.

f, is in MHz, where ω represents the angular frequency, $2\pi f$, and ϵ_0 is the permittivity of free space (8.854×10^{-12} F·m^{-1}). These dielectric properties have been defined previously, based on both electrical-circuit concepts (Nelson 1965) and electromagnetic field concepts (Nelson 1973a). The dielectric properties of grain are frequency and temperature dependent as well as moisture dependent (Nelson 1973a).

Most electrical grain moisture meters use circuits that operate at frequencies between about 2 and 20 MHz to sense variations in moisture content. Because dielectric properties of grain vary considerably with frequency (Nelson and Stetson 1976), it seems reasonable to explore the moisture dependence of these properties in other frequency ranges. This study was conducted to obtain basic information on the dielectric properties of corn to help determine whether there is a basis for improving the reliability of electrical measurements of moisture content in high-moisture grain.

MATERIALS AND METHODS

Corn, *Zea mays* L., samples for the measurements were picked by hand at relatively high moisture contents from the University of Nebraska experimental farms and from University of Nebraska Agronomy Department corn nursery plots. All samples were of known genetic background. The 25 lots obtained included 21 yellow-dent field corn samples, 1 white-dent variety, 2 flint-type varieties, and 1 floury-endosperm variety.

Ear-corn lots were packaged in large plastic bags and placed in storage at 4° C (40° F) to prevent loss of moisture and to retard mold development and spoilage. Within a few days, the ears were shelled by hand. The regions near the ends of the ears were excluded to limit variation in kernel size and shape. The shelled corn for each lot was sealed in wide-mouthed, 1-gal glass jars, with enough airspace left to permit mixing of the contents by rotation of the jar, and returned to storage at 4° C. Each lot was mixed frequently during the course of the measurements. When measurements were to be performed on a corn lot, the lot was thoroughly mixed in the gallon jars and a ⅔-pt sample was removed, sealed in a pint mason jar, and permitted to come to room temperature (24° C, 75° F). Samples for electrical measurements, kernel density measurement, and moisture-content determinations were drawn from the pint-jar sample after it too was thoroughly mixed. The entire lots in the gallon jars were also permitted to come to room temperature once at each moisture level for an official test-weight determination (U.S. Department of Agriculture 1953).

After all measurements were completed at each moisture level, the corn from the gallon jars was

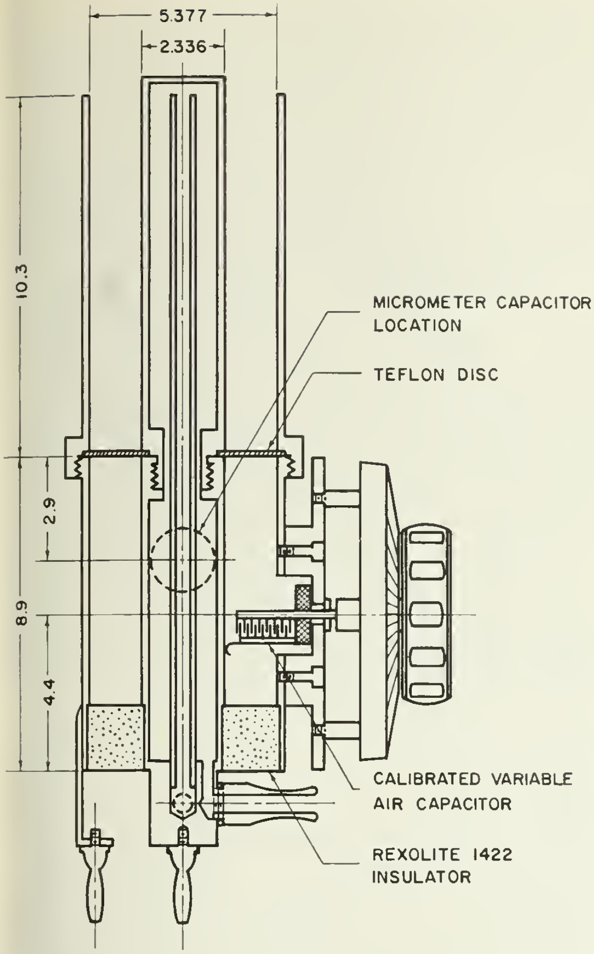


FIGURE 2.—Sectional view showing details of construction of sample holder used with Q-meter for measurements at 20 MHz. Dimensions in centimeters.

spread out in shallow pans in a layer about one kernel deep, and the lots were permitted to dry at 24° C and 40 percent relative humidity (RH) for a specified time to reach the next lower desired moisture content. They were then poured through an airstream created by a 16-in electric fan to remove any lightweight loose particles and chaff, resealed in gallon jars, and returned to cold storage (4° C). After being dried, each lot was given at least 7 days for moisture distribution to equilibrate before measurements were taken on that lot again. Drying time at 24° C and 40 percent RH ranged from a few hours to several days depending upon the moisture level of the lot. The moisture level for the final measurements was the equilibrium moisture content at 24° C and 40 percent RH. At this final moisture content, dimensional measurements of the kernels were determined for each of the 25 lots, and subsamples were taken for fat acidity and protein determinations.

Electrical Measurements

Measurements of the dielectric properties of grain samples were taken at three frequencies: 20 and 300 MHz, and 2.45 GHz. Different measurement systems and principles of measurement were used at each frequency. A Boonton Q-meter, type 160-A, and a reactance variation method (Nelson et al. 1953) were used for measurements at 20 MHz. At 300 MHz, a General Radio admittance meter, type 1602B, was used with a sample holder modeled as sections of coaxial transmission lines (Stetson and Nelson 1970). The short-circuited line technique of Roberts and von Hippel (1946) and a Rohde and Schwarz power signal generator, nonslotted line, and standing-wave indicator (Nelson 1973b) were used for measurements at 2.45 GHz.

New sample holders were designed and constructed for each of these systems especially for measurements on the corn lots. Coaxial-line sample holders of identical cross-sectional dimensions for each system were used to provide common sample volumes and bulk densities for measurements of the corn samples at each frequency. The three sample holders are pictured in figure 1.

Construction details of the new sample holder for use with the Q-meter are shown in figures 2 and 3. The design included not only a variable air capacitor to restore the capacitance attributable to the sample when it is removed from the sample holder, but also a second variable capacitor formed by the spindle of a micrometer head that projects into a brass sleeve with a clearance of about 0.018 cm. This design provides a more precise measurement for the width of the resonance peak of the voltage amplitude-versus-capacitance curve than does the use of the vernier capacitor of the Q-meter and makes possible more reliable measurements of the loss tangent and loss factor. Provision for temperature control was also designed into the new sample holder. Liquid from a temperature-controlled circulator can be pumped through the interior of the center conductor of the sample holder and through a copper tubing coil that can be placed around the outer conductor of the sample holder.

For 300-MHz measurements on corn samples, a sample holder was assembled using the lower section of the sample holder described previously for use with the General Radio admittance meter (Stetson and Nelson 1970) and the top section of the sample holder described previously for use with the

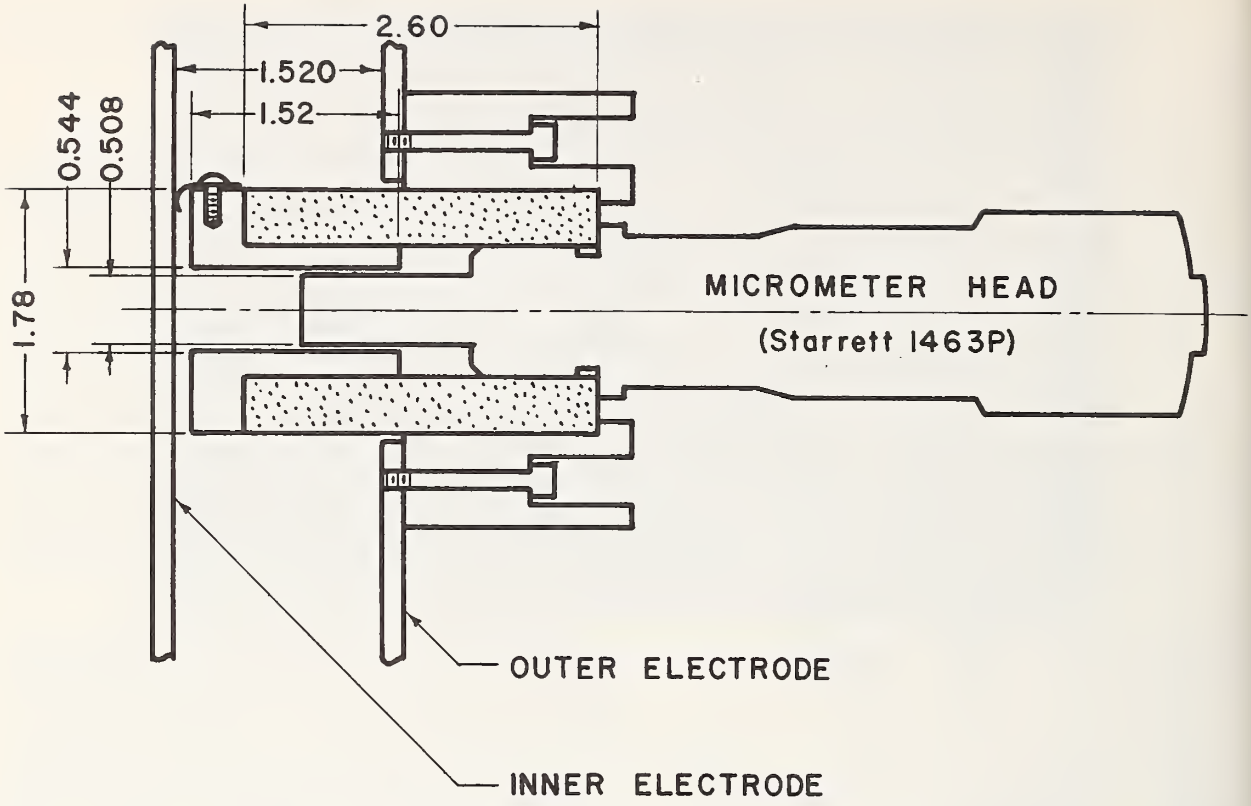


FIGURE 3.—Details of construction and mounting of micrometer capacitor in Q-meter sample holder. Dimensions in centimeters.

Boonton type 250-A RX meter (Jorgensen et al. 1970). The values of the lumped-circuit model parameters (Stetson and Nelson 1970) were readjusted to provide proper values for the dielectric constants and loss factors for measurements on air, Rexolite 1422, dodecanol, and heptanol. Calculated values for the dielectric properties agreed within a few percent with accepted values for these materials.

The new sample holder for measurements at 2.45 GHz was built with a step transition designed to minimize reflections from the discontinuity (Kraus 1960) where the dimensions of the 50-ohm coaxial line changed from the Rohde and Schwarz 21-mm air line to the 50-ohm characteristic-impedance sample holder of larger dimensions. Details of the new sample holder, which was designed to attach directly to the Rohde and Schwarz nonslotted line, are shown in figure 4. It was also designed to permit the temperature of the sample to be controlled by circulating a liquid through the center conductor and through a coil around the outer conductor.

Before assembly, brass parts of all sample holders were silver plated to reduce electrical conduction losses. The inside diameter of the outer conductor was then measured as 5.377 cm, and the outside diameter of the inner conductor was measured as 2.336 cm. This provided a sample cross-sectional area of 18.420 cm^2.

The volume of sample required to fill properly the admittance-meter sample holder for measurements at 300 MHz was 116.485 cm^3. The sample height in the sample holder was therefore 6.32 cm. The grain samples filled the sample holder for measurements at 300 MHz to the top, even with the top of the electrodes, before the open-circuit-termination cap was put on. Sample height gages were machined from Rexolite 1422 to permit easy adjustment of sample height in the sample holders used for measurements at 20 MHz and 2.45 GHz. In this way, the same sample density could be obtained for measurements at all three frequencies.

The same grain sample was used for measurements at all three frequencies. It was weighed to permit sample bulk-density calculation. Measurements were repeated three times at each frequency. The sample was removed from the sample holder and then replaced for each successive measure-

ment. Dielectric properties were calculated on a Wang 700B programmable calculator for the 20- and 300-MHz measurements. Dielectric properties for 2.45-GHz measurements were calculated from waveguide measurements data on an IBM 360/65 computer by a general program described previously (Nelson et al. 1972; Nelson et al. 1974). Values for the three repeated measurements at each frequency were averaged for each sample.

Moisture-Content Determination

Three different moisture-determination methods were planned for the study of dielectric properties of corn. One is the method specified in the Official Grain Standards of the United States (February 1970), that is, drying unground, 15-g samples in 55-mm-diameter aluminum moisture dishes in a forced-air oven at 103° C for 72 h. The second oven method involves drying 2-g ground samples in the same moisture dishes for 3 h at 130° C. In both methods, the aluminum moisture dishes were heated at the prescribed temperature for at least 1 h and cooled in a desiccator before initial weighing, covers were placed on dishes with samples before removal from the oven after the sample drying period, and dishes with samples were cooled in a desiccator before reweighing. For the method in which samples are ground before drying, two-stage procedures were used whenever moisture content exceeded 13 percent, wet basis. The third method planned was the Karl Fischer titration method, which was to be run on the samples by the National Bureau of Standards (NBS).

Samples for moisture tests were drawn from the pint-jar samples for the corn lot at the time that electrical measurements were completed. Three moisture dishes, after being weighed empty, were filled heaping full, weighed, placed on top of the oven for the first stage of the 3-h moisture test and dried overnight or longer. At the same time, 45 g of corn was sealed in a ½-pt jar to hold until Friday for the 72-h tests, which were usually run over the weekend. At the completion of the first stage for the 3-h test, each of the three replicates was weighed and then sealed separately in ½-pt or 1-pt jars for moisture distribution to equilibrate for about 1 wk before the second stage (3-h test) was run. When the 2-g ground samples had been taken for each of the three replicates, the three jars were resealed and sent to the NBS Gaithersburg Laboratories for the Karl Fischer tests.

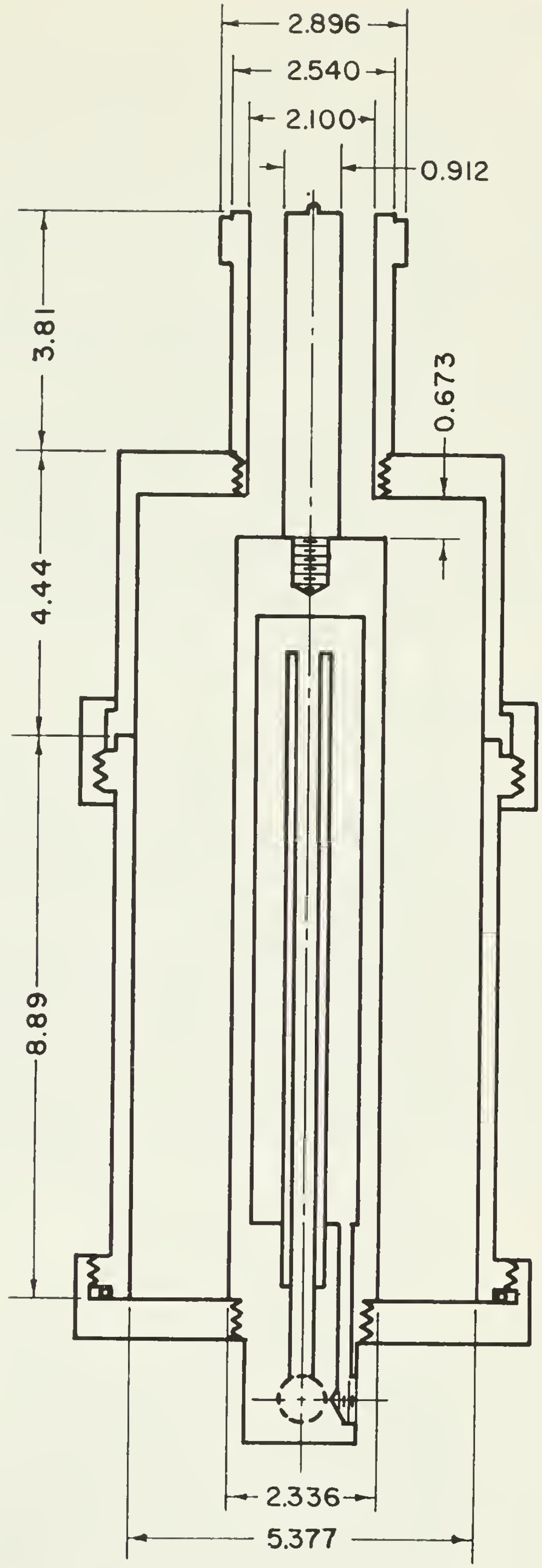


Figure 4.—Sectional view of coaxial sample holder used for short-circuited line measurements at 2.45 GHz. Dimensions in centimeters.

Kernel Density and Weight Measurements

In addition to the test-weight determinations and the sample bulk densities calculated from electrical-measurement sample-holder volume and sample weights, the kernel densities were determined for all seed lots at each moisture level. A 25-g sample was drawn from the pint jars at the same time that samples were taken for moisture tests, and the volume occupied by the kernels in this sample was measured with a Beckman model 930 air-comparison pycnometer. Volumes obtained for these measurements were averages of three measurements, and, along with the sample weights, were used to calculate kernel densities. The number of kernels in the 25-g sample was counted so that a mean kernel weight could also be obtained. Calibration of the pycnometer was checked frequently during the course of the experiment to maintain the calibration.

Kernel Dimensions and Chemical Analyses

At the conclusion of the measurement sequence, when the sample moisture contents were in equilibrium at 24° C and 40 percent RH, the length, width, and thickness of each kernel in a 50-kernel sample were measured with a dial-type vernier caliper, and mean values were calculated. At this time also, samples from each lot were taken for chemical analyses that included determinations for protein and fat acidity (Association of Official Analytical Chemists 1970). Colored slide pictures were taken of each lot also at this time for possible future use in distinguishing other characteristics of the different corn lots.

ANALYSES, RESULTS, AND DISCUSSION

The 25 corn lots on which the various measurements were taken are described in table 1. The moisture-content range over which electrical properties and other data were obtained is also given in table 1, along with density and kernel dimension and weight data obtained at the final moisture level (nearly 10.5 percent for all corn lots). Fat acidity values were all well below the level customarily used for indication of storage deterioration (22 mg KOH/100 g) (Baker et al. 1957), and so the corn samples all retained their good quality throughout the measurement study. Photographs illustrating variation in kernel shape and appearance are shown in figure 5.

Bulk-density values are those obtained from the weight and volume of corn samples used in the sample holders for the dielectric properties measurements. These were deemed more meaningful than the test-weight determinations, because standard test-weight measurements on high-moisture corn are quite variable, and the bulk densities during the electrical measurements are the most significant values to use for this study. Bulk densities in the sample holders during measurement were somewhat lower than densities determined by official test-weight procedures, especially at lower moisture contents. Linear regression analysis of bulk density in the sample holder, ρ_b, on bulk density from test-weight measurements, ρ_t, over all yellow-dent samples yielded the following relationship with a correlation coefficient of 0.907: $\rho_b = 0.147 + 0.767\ \rho_t$, where ρ_b and ρ_t are bulk densities in grams per cubic centimeter.

Moisture Measurements

Moisture-content values used for the presentation of data are those values obtained from the 3-h drying method on ground samples. Karl Fischer determinations were not obtained on enough samples for meaningful comparison, but earlier comparisons gave reasonably good agreement between Karl Fischer determinations and the 3-h oven method (F. Jones, personal communication, 1974). Since both 3-h and 72-h oven-method tests were performed on every sample used in these studies, results were compared for the two oven methods. The 3-h test at 130° C with ground samples always gave a higher moisture content value than the 72-h test at 103° C on unground samples. Considering all 25 corn lots, there were 163 moisture-test observations for each of the 2 oven methods. Because there were greater numbers of observations at lower moisture contents, the observations were grouped into the following moisture ranges with the indicated number of observations for each range (M represents moisture content in percent): $10<M<11$, 24; $11\leq M<13$, 25; $13\leq M<15$, 27; $15\leq M<17.5$, 25; $17.5\leq M<20$, 18; $20\leq M<25$, 17; $25\leq M<30$, 10; $30\leq M<35$, 9; $M\geq 35$, 8. Differences between moisture contents obtained with the 3-h and 72-h tests were calculated, and, within each of the nine moisture ranges indicated, mean values and standard deviations were calculated for the 3-h moisture contents and for the differences between

(*Continued on page 14.*)

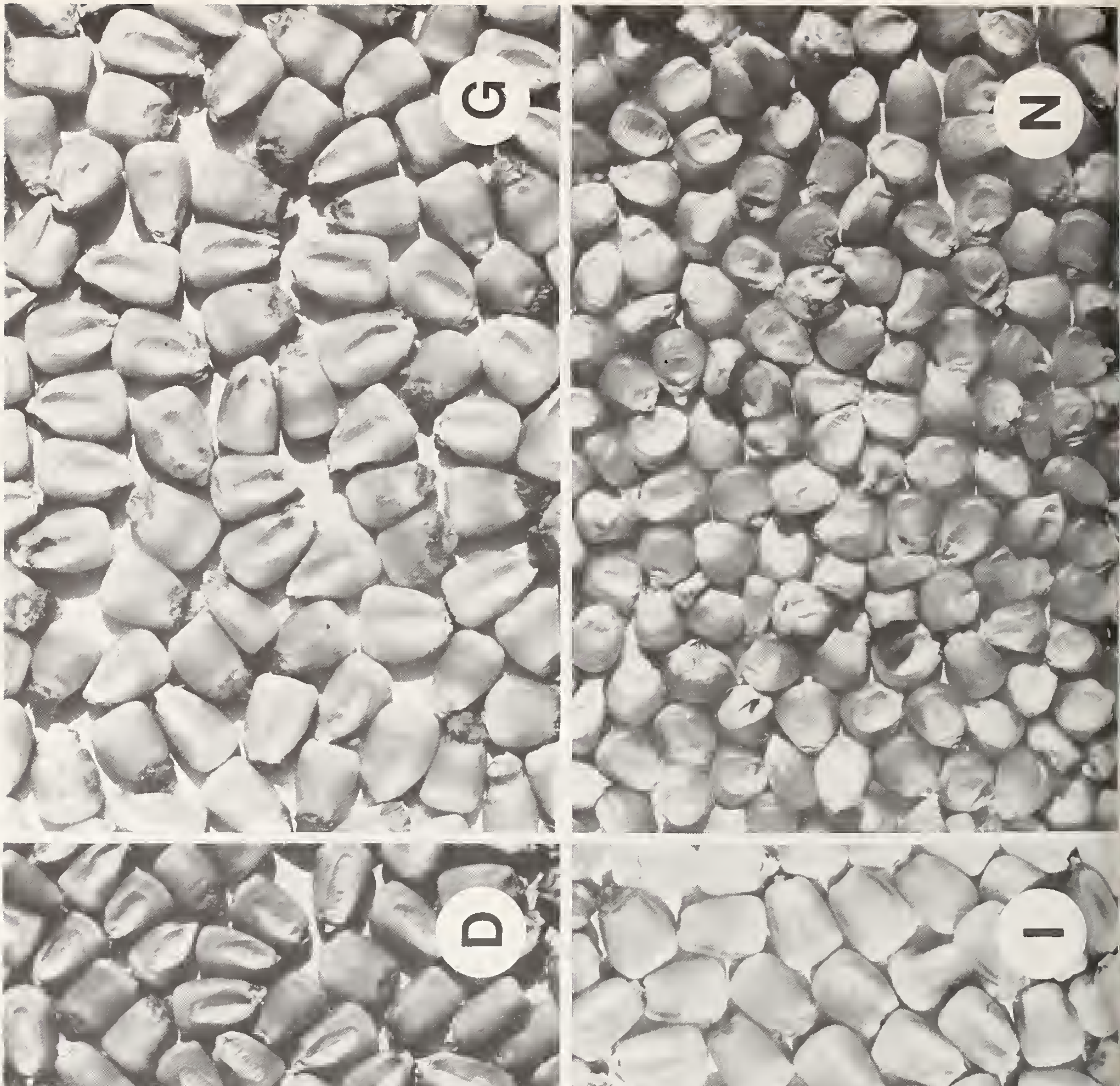
Table 1.—Corn lot descriptions, range of moisture content studied, and selected properties

Lot	Hybrid or genotype[1]	Location[2]	Harvest date (all 1975)	Moisture range (%)	Properties at 10 percent moisture, wet basis[3]							
					Bulk density (g/cm³)	Kernel density (g/cm³)	Kernel weight (mg)	Kernel dimensions			Crude Protein (%)	Fat acidity (mg KOH/100 g)
								Length (mm)	Width (mm)	Thickness (mm)		
A	'Dekalb XL75'	1	Sept. 8	10.3–42.6	0.728	1.294	228.9	11.98	7.34	3.61	10.75	13.90
B	'Pioneer 3390'	1	..do	10.3–31.0	.732	1.285	295.4	12.51	7.18	4.56	10.69	8.56
C	'Dekalb XL72A'	1	..do	10.7–37.1	.724	1.257	289.7	11.90	8.27	4.36	10.50	11.50
D	'Pioneer 3388'	1	..do	10.4–22.9	.743	1.284	246.6	11.60	7.31	4.25	10.06	8.70
E	'NC+SX85'	2	..do	10.3–35.4	.734	1.268	321.1	12.56	8.69	4.34	9.75	8.52
F	'UN Foundation Seed 6–11'	3	Sept. 9	10.5–36.5	.725	1.229	282.1	11.99	8.43	4.23	9.44	9.74
G	'Pioneer 3388'	3	..do	10.7–40.9	.710	1.282	337.9	12.72	8.77	4.29	9.38	9.31
H	'N139' × 'B73'	4	Sept. 16	10.7–33.7	.744	1.334	297.5	13.29	7.35	4.00	7.75	6.95
I	'N7AW' × '(103 × T11) 29–4–1'	4	..do	10.3–33.6	.765	1.313	305.6	12.43	8.74	3.73	8.19	6.95
J	'N28' × 'N132'	5	..do	10.4–26.2	.748	1.285	314.4	12.78	7.77	4.36	9.31	6.70
K	'N162' × 'N132'	5	..do	10.4–19.8	.775	1.315	301.9	12.43	7.43	4.39	9.00	6.18
L	'N7A' × 'N28'	5	..do	10.5–24.9	.750	1.282	367.6	13.62	8.47	4.44	9.31	8.01
M	'Mo17' × 'B73'	5	..do	10.6–17.5	.750	1.276	334.2	12.47	8.04	4.54	10.19	5.83
N	'Columbia MVA'	5	..do	10.4–31.9	.791	1.345	218.7	9.30	7.89	4.49	11.88	7.66
O	'Rainbow Flint'	5	..do	10.3–16.5	.735	1.267	252.7	8.42	9.36	5.73	11.69	9.14
P	'Gourdseed' × 'Mandan Flint'	5	..do	10.3–21.6	.627	1.205	333.5	10.88	10.53	5.39	11.94	19.30
Q	'N28' × 'Mo17'	5	Sept. 22	10.5–19.6	.755	1.288	371.7	12.59	8.74	4.61	10.19	5.92
R	'N7A' × 'Mo17'	5	..do	10.8–17.7	.746	1.228	358.9	12.93	8.92	4.53	9.19	6.00
S	'N132' × 'B73'	5	..do	10.8–18.0	.762	1.293	287.6	13.31	6.93	3.94	8.63	6.09
T	'N31' × 'N132'	5	..do	10.7–17.3	.715	1.253	344.4	13.33	8.05	4.62	9.81	6.53
U	'Mo17' × 'N132'	5	..do	10.7–16.9	.734	1.257	363.2	13.00	8.84	4.48	8.94	7.14
V	'N2' × 'N143'	5	..do	10.6–14.5	.791	1.311	304.1	12.16	7.56	4.42	9.56	7.84
W	'H95' × 'N132'	5	..do	10.6–15.8	.771	1.293	289.2	12.34	7.72	4.24	9.25	6.79
X	'B59' × 'N152'	5	..do	10.6–16.4	.708	1.263	327.2	12.99	8.28	4.51	9.81	5.13
Y	'B14A' × 'B57'	4	Oct. 3	10.3–26.4	.722	1.258	310.6	11.95	8.27	4.58	11.88	5.57

[1]All lots were yellow-dent field corn, except: I, white-dent field corn; N and O, flint corn; P, floury endosperm.

[2]University of Nebraska farms and plots: 1, Rogers farm; 2, agricultural engineering farm; 3, Mead field laboratory; 4, agronomy plots (Stevens Creek); 5, agronomy corn nursery plots.

[3]Density, weight, and dimension values are those for the lower figure shown in the "moisture range" column. Crude protein (mg N/g × 0.625) and fat-acidity values are corrected to 10.0 percent moisture.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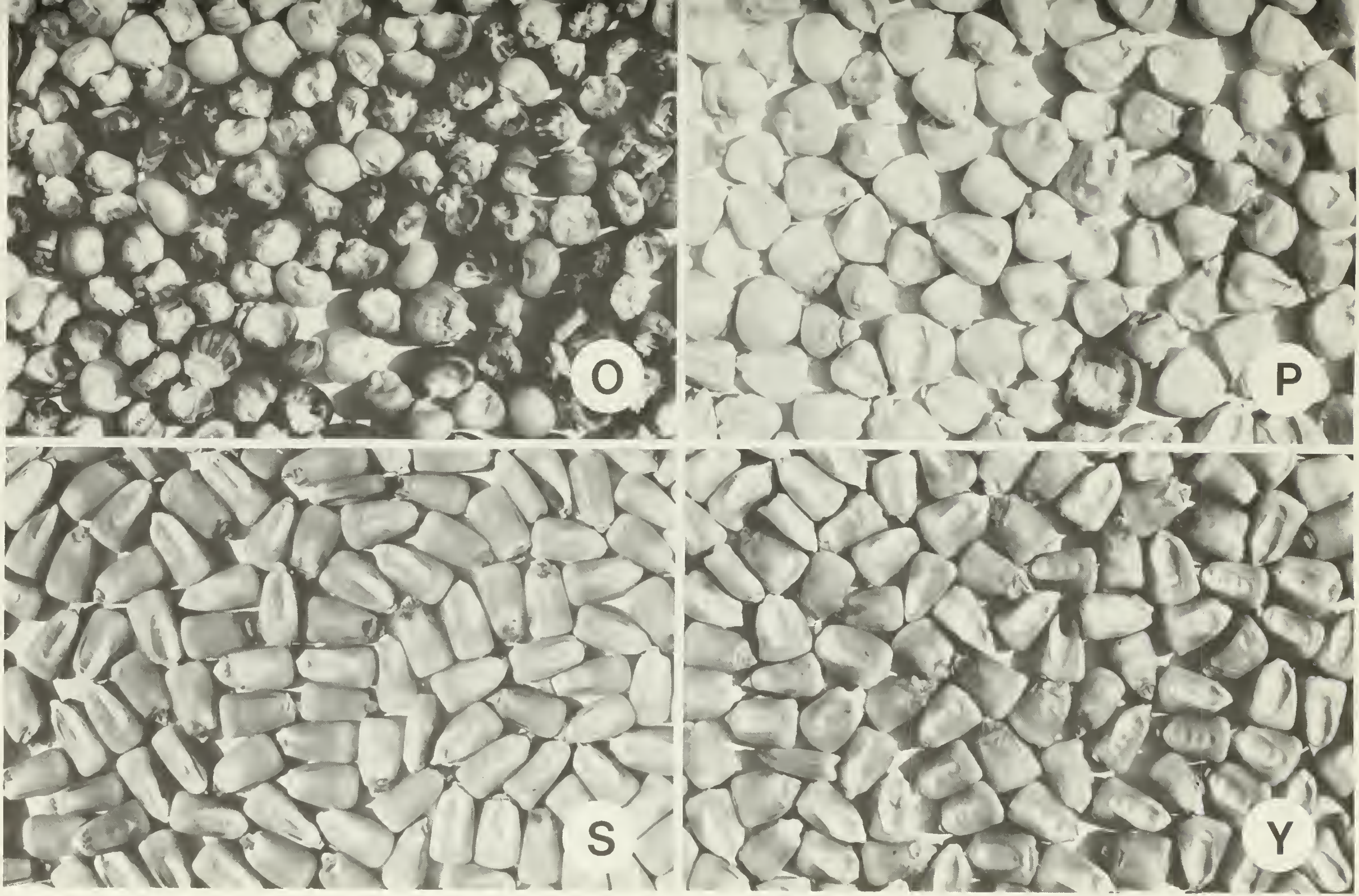


FIGURE 5.—Variation in kernel appearance: 1st row: lots D and G; 2d row: lots I and N; 3d row: lots O and P; 4th row: lots S and Y.

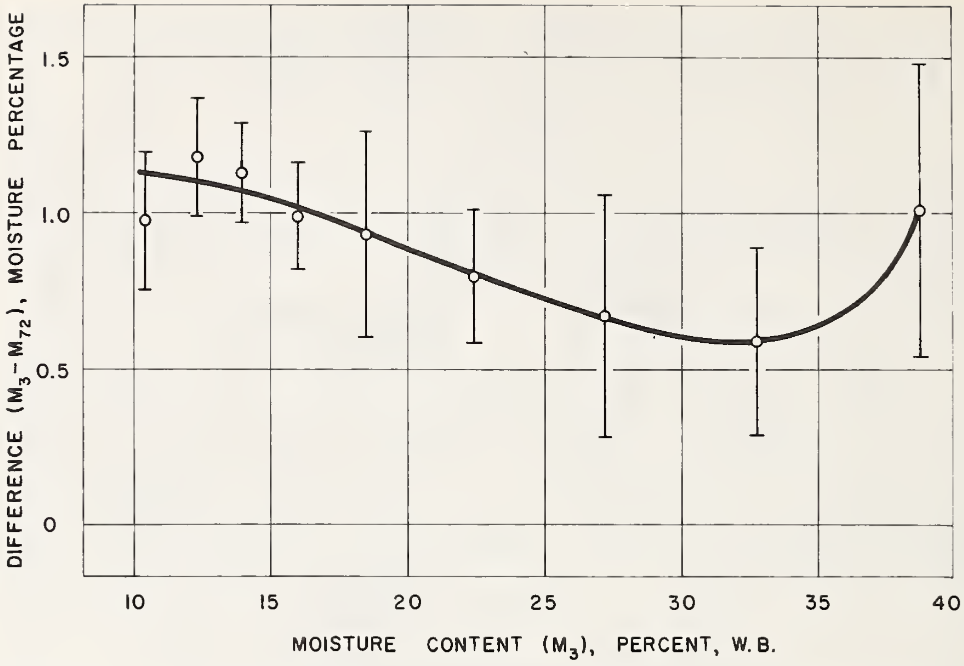


FIGURE 6.—Differences between moisture contents determined by 3-h (M_3) and 72-h (M_{72}) oven-moisture methods for shelled field corn (means ±1 standard deviation).

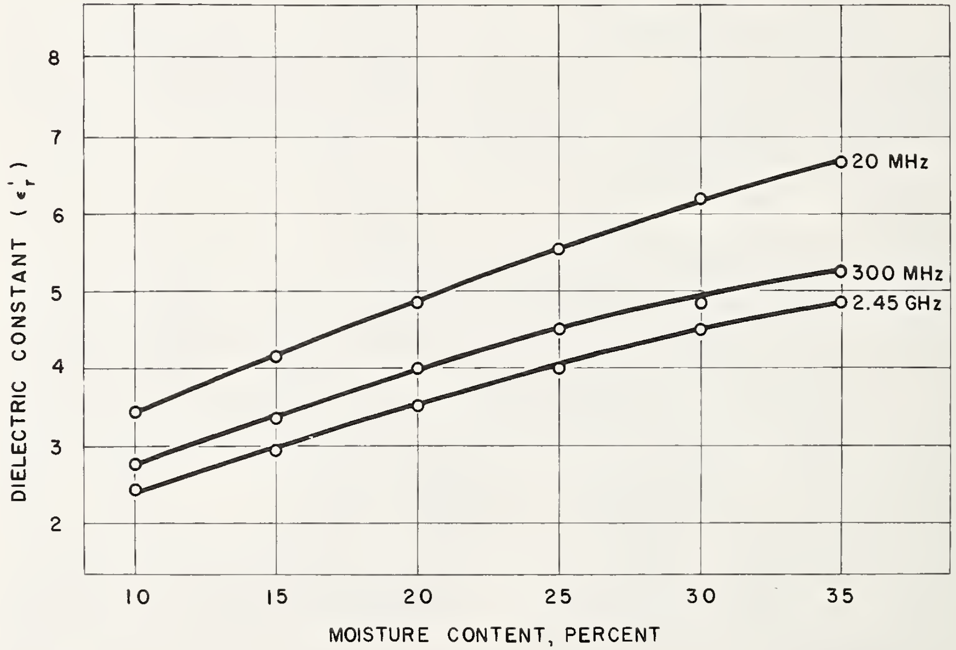
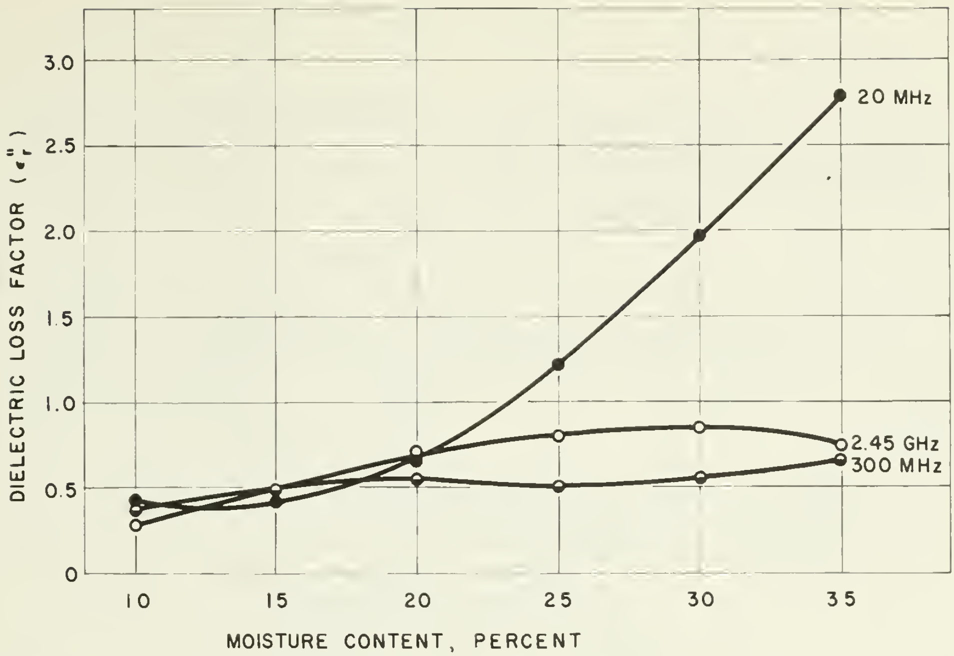
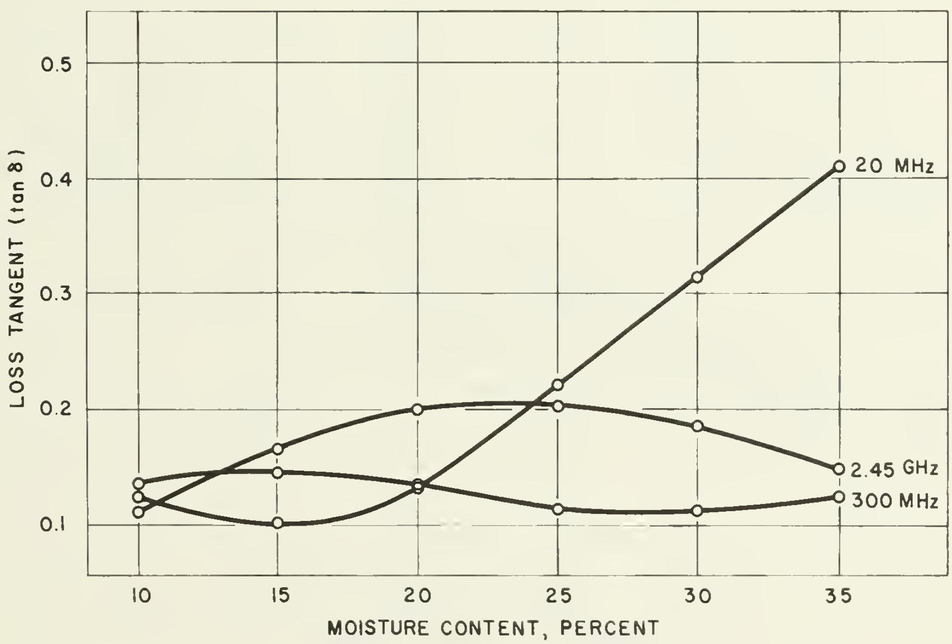


FIGURE 7.—Moisture dependence of the dielectric constant of shelled yellow-dent field corn at 24° C and indicated frequencies. Points are mean values from curves for different lots represented.



URE 8.—Moisture dependence of the dielectric loss factor of shelled yellow-dent field corn at 24° C and indicated frequencies. Points are mean values from curves for different lots represented.



URE 9.—Moisture dependence of the loss tangent of shelled yellow-dent field corn at 24° C and indicated frequencies. Points are mean values from curves for different lots represented.

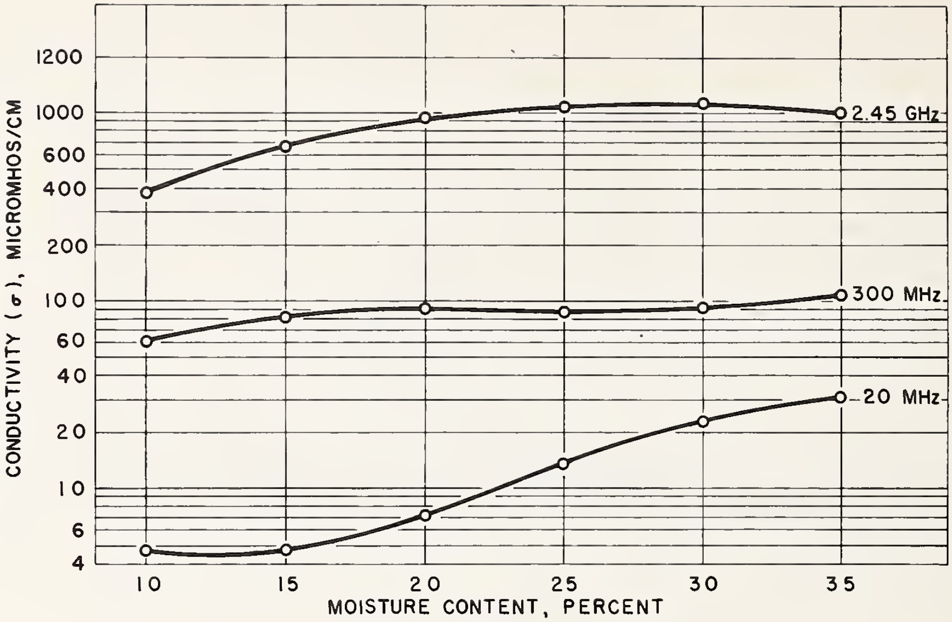


FIGURE 10.—Moisture dependence of the electrical conductivity of shelled yellow-dent field corn at 24° C and indicated frequencies. Points are mean values from curves for different lots represented.

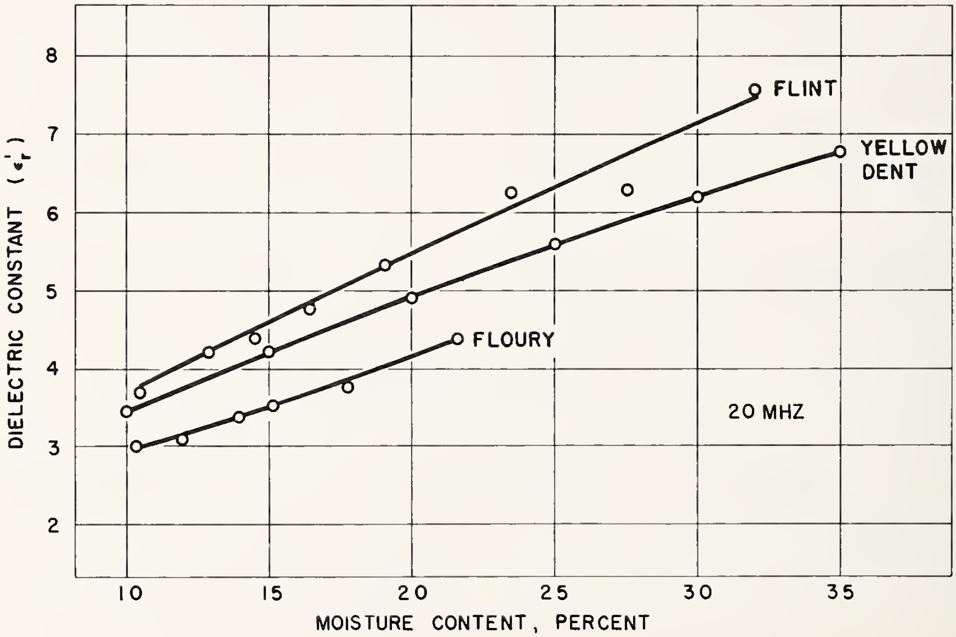


FIGURE 11.—Comparison of dielectric constants of a flint-type and floury-endosperm corn with mean dielectric-constant values of yellow-dent corn at 20 MHz. Differences probably resulted from differences in bulk density.

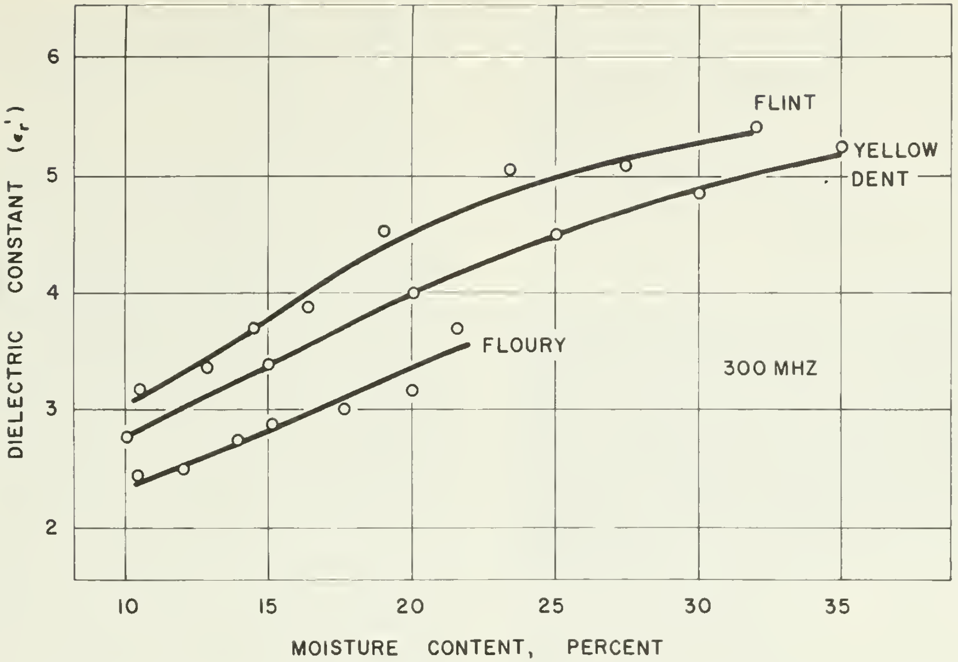


FIGURE 12.—Comparison of dielectric constants of a flint-type and floury-endosperm corn with mean dielectric-constant values of yellow-dent corn at 300 MHz. Differences probably resulted from differences in bulk density.

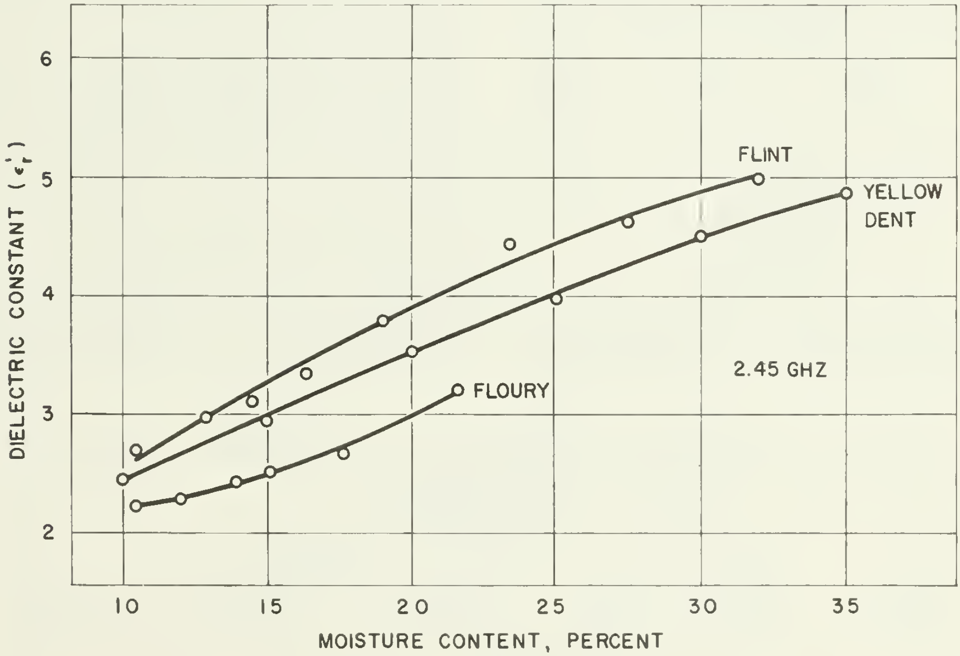


FIGURE 13.—Comparison of dielectric constants of a flint-type and floury-endosperm corn with mean dielectric-constant values of yellow-dent corn at 2.45 GHz. Differences probably resulted from differences in bulk density.

the two methods. Results of the comparison are summarized in figure 6. The 3-h method gave moisture contents about 1 percentage point higher than the 72-h method in the 10- to 20-percent range and at moisture levels above 35 percent. In the range between 20 and 35 percent, differences were generally somewhat less than 1 percent moisture.

Dielectric Properties

Values obtained for the dielectric constant, ϵ_r', and loss factor, ϵ_r'', at each of the three frequencies (20 MHz, 300 MHz, and 2.45 GHz) were plotted against moisture content (3-h method) for each corn lot. Smooth curves were drawn through the points determining the plots for ϵ_r'-versus-moisture content and ϵ_r''-versus-moisture content. Values for ϵ_r' and ϵ_r'' were taken from the curves at each 5-percent moisture-content interval from 10 to 35 percent, and these values were averaged over all the yellow-dent corn lots. The mean values of ϵ_r' and ϵ_r'' at 5-percent moisture-content intervals are therefore representative of yellow-dent corn, and their relationships with moisture content are illustrated in figures 7 and 8. Values for the loss tangent, tan δ, and the conductivity, were calculated from the 5-percent moisture-interval values of ϵ_r' and ϵ_r'', and their dependence on moisture content is shown in figures 9 and 10.

The dielectric properties of flint-type lots and the floury corn lot were noticeably different from the yellow-dent corn lots. The comparisons of their dielectric constant values (lots N and P) with those of the yellow-dent corn properties are shown for frequencies of 20 MHz, 300 MHz, and 2.45 GHz in figures 11, 12, and 13, respectively. Lot N had the highest ϵ_r' values, and lot P had the lowest ϵ_r' values of all the lots measured. At all three frequencies, the dielectric constant of flint corn was higher than that of yellow-dent corn, and the dielectric constant of the floury-endosperm corn was lower than that of yellow-dent corn of comparable moisture contents. The floury corn (lot P) had lower bulk and kernel densities than any of the yellow-dent lots, and the flint corn (lot N) had higher densities than most of the dent corn lots. These differences in density probably account for the differences in dielectric constant between the three types of corn.

Standard deviations and coefficients of variation (sample standard deviation divided by the sample mean) were calculated from the 5-percent moisture-interval values of ϵ_r' and ϵ_r'' taken from the initial plots. These coefficients of variation provide a measure of the variation in ϵ_r' and ϵ_r'' values observed over the 25 corn lots at each moisture level and for each frequency at which measurements were taken. Results are shown in table 2. Coefficients of variation ranged from about 4 to 6 percent for the dielectric constant and were generally higher and less consistent for the dielectric loss factor. There was no real difference in the variation among lots noted for the dielectric properties at the

Table 2.—Variation in dielectric properties of 25 corn lots[1]

Moisture content (%)	Coefficient of variation (%)					
	20 MHz		300 MHz		2.45 GHz	
	ϵ_r'	ϵ_r''	ϵ_r'	ϵ_r''	ϵ_r'	ϵ_r''
10	5.2	9.2	5.6	10.0	4.7	12.7
15	5.4	6.7	5.4	7.8	4.5	8.6
20	5.5	8.7	6.3	9.8	5.7	7.6
25	5.5	11.0	5.7	8.3	5.0	7.2
30	5.8	20.8	4.4	12.9	5.4	6.2
35	6.3	6.2	6.1	8.6	4.0	5.4

[1]At the higher moisture contents, fewer than 25 lots are represented by these data (see table 1).

Table 3.—Variation in densities and dielectric properties of 21 yellow-dent field corn lots[1]

Moisture Content (%)	Coefficient of variation (%)							
	Bulk density	Kernel density	Dielectric properties					
			20 MHz		300 MHz		2.45 GHz	
			ϵ_r'	ϵ_r''	ϵ_r'	ϵ_r''	ϵ_r'	ϵ_r''
10	3.6	2.1	4.1	8.3	4.4	9.7	3.3	13.1
15	2.4	1.6	3.4	6.2	4.1	4.9	3.5	6.9
20	2.5	1.2	2.5	6.7	4.2	7.4	3.4	5.0
25	4.1	1.5	e.6	12.0	5.3	2.1	3.7	7.8
30	2.4	1.5	3.4	22.5	2.6	11.2	3.9	5.7
35	3.3	1.5	5.9	6.2	4.3	8.6	3.0	5.4

[1]At the higher moisture contents, fewer than 21 lots are represented by these data (see table 1).

three different frequencies. Coefficients of variation for the dielectric properties and bulk and kernel densities of 21 yellow-dent corn lots are shown in table 3. Coefficients of variation are generally somewhat smaller when the flint, floury-endosperm, and white-dent samples are not included in the population considered.

The influence of sample bulk density on the dielectric constant is shown in figures 14, 15, and 16 for 20-MHz, 300-MHz, and 2.45-GHz measurements, respectively. These data were obtained on a few corn lots at different moisture levels by filling the sample holders loosely and normally and by completely settling the samples to provide three different bulk densities. Yellow-dent lots used were A (33.4 percent), B (22.9, 12.2, and 10.3 percent), D (19.5 percent), and R (17.7 percent). Lot N was used for the flint corn data shown, and lot P was the only floury-endosperm lot available. At each frequency and all moisture levels, the relationship between bulk density and dielectric constant seemed to be linear for this limited density range. The slope of the curves increases as moisture content increases, showing that the influence of bulk density is enhanced by moisture. The degree of possible variation in bulk density also increases with moisture content.

The temperature dependence of the dielectric properties was studied on a few of the corn lots. Measurements at temperatures of 25°, 30°, 40°, 50°, and 60° C were taken at all three frequencies (20 MHz, 300 MHz, and 2.45 GHz). Samples from lot Q were measured at moisture contents of 18.9, 15.2, and 10.5 percent, from lot S at 17.7, 14.5, and 10.8 percent, and from lot U at 10.7 percent. Results of these measurements are summarized for ϵ_r' in figure 17, where values for lot Q are shown only for 10.5 and 18.9 percent moisture. Similar curves were obtained for the other lots and moisture levels. The dependence of the dielectric constant on temperature is nearly linear in this temperature range at low moisture levels, but some departure from linearity occurs at higher moisture levels, particularly at the lower frequencies. Dielectric-loss-factor data were much less regular, because the loss factor generally may either increase or decrease with frequency or moisture content.

Density Relationships

The bulk densities of corn samples from each lot used for the electrical measurements were plotted against the moisture contents measured by the 3-h oven tests for each moisture level, and smooth curves were drawn through the points. Bulk-density values were taken from the curves for each

(*Continued on page 18.*)

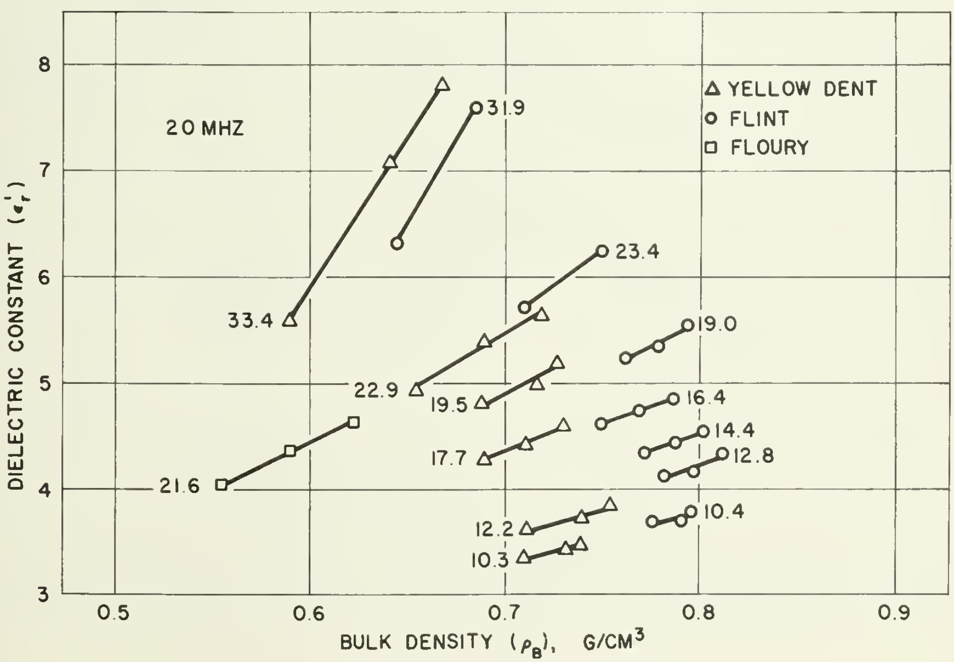


FIGURE 14.—Dependence of the dielectric constant at 24° C and 20 MHz on bulk densities of shelled yellow-dent, flint, and floury-endosperm corn.

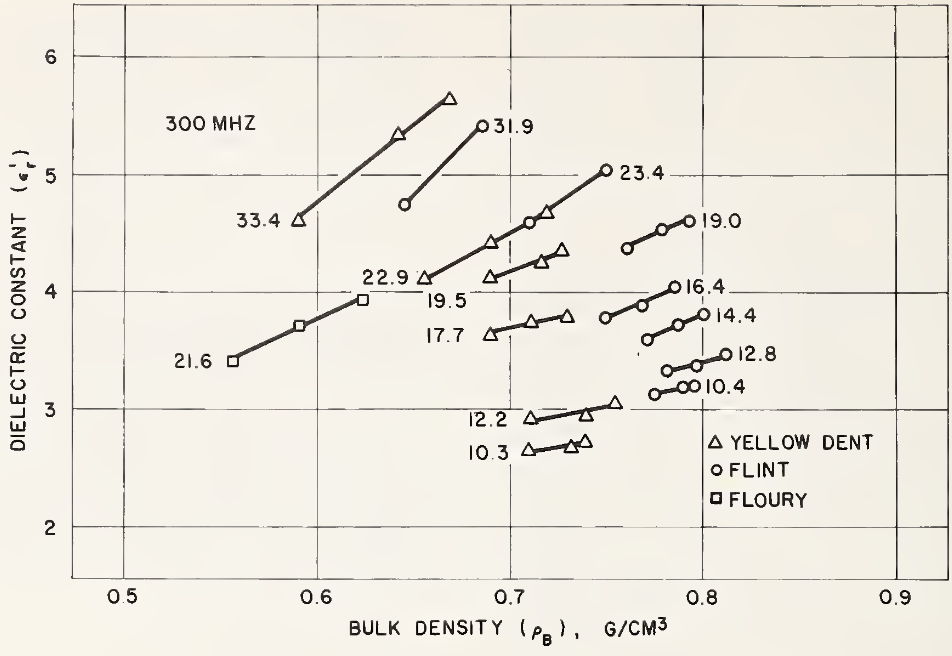


FIGURE 15.—Dependence of the dielectric constant at 24° C and 300 MHz on bulk densities of shelled yellow-dent, flint, and floury-endosperm corn.

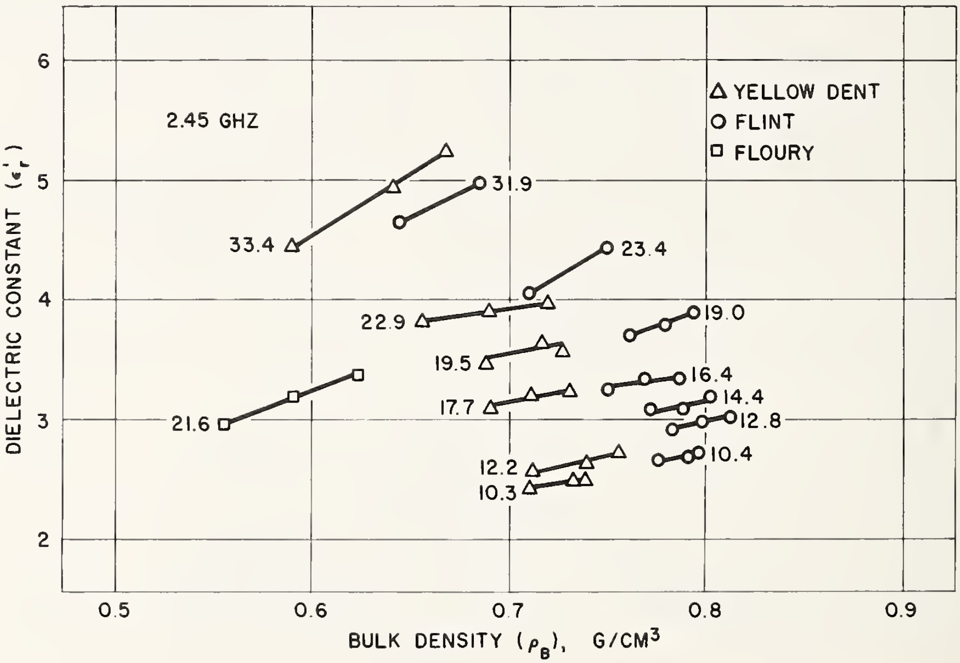


FIGURE 16.—Dependence of the dielectric constant at 24° C and 2.45 GHz on bulk densities of shelled yellow-dent, flint, and floury-endosperm corn.

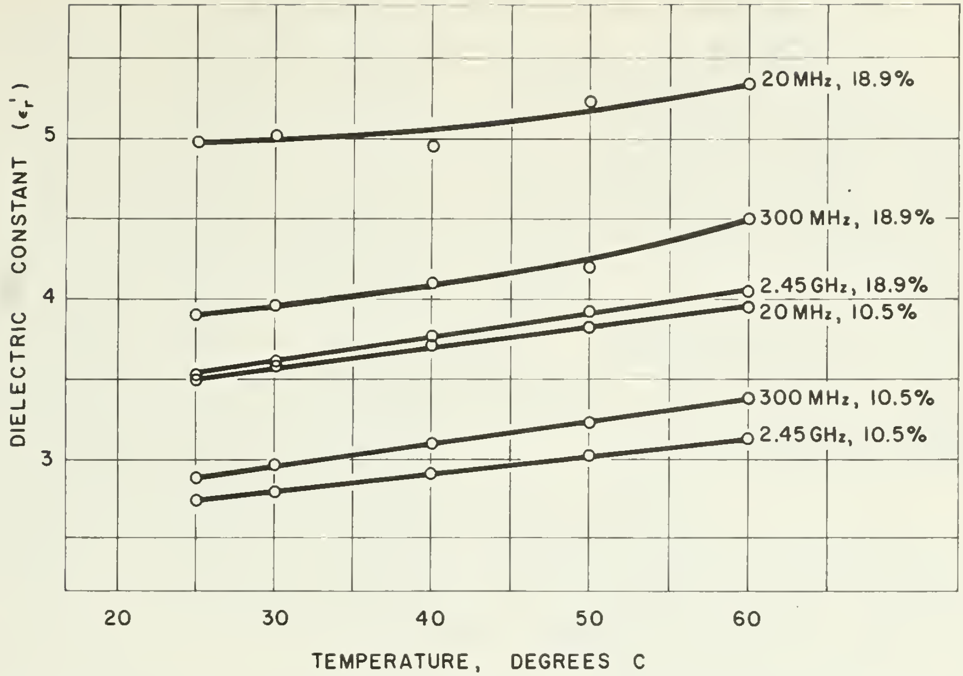


FIGURE 17.—Temperature dependence of the dielectric constant of yellow-dent field corn at indicated frequencies and moisture contents.

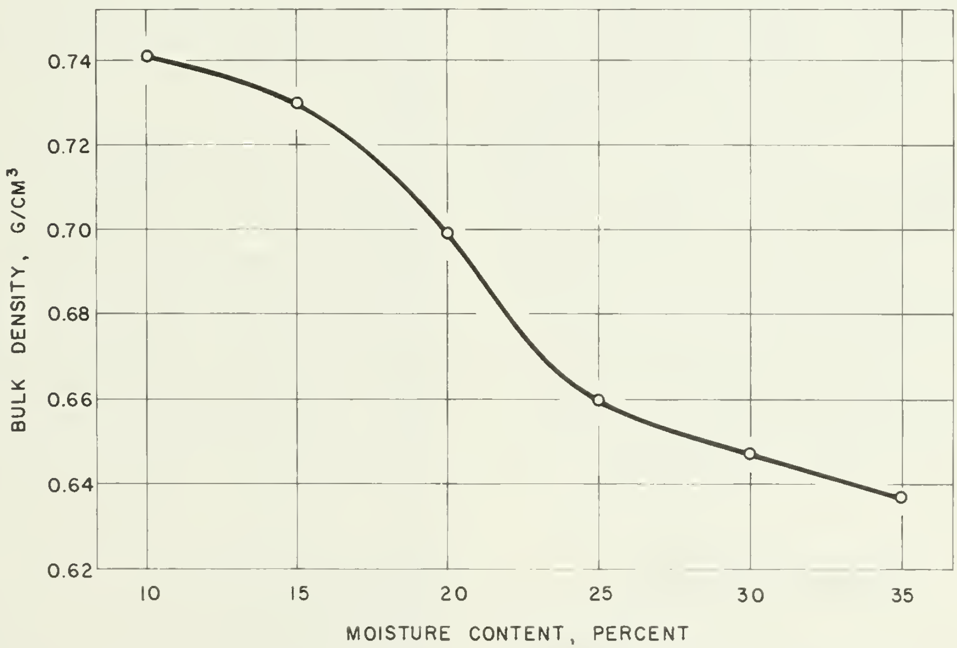


FIGURE 18.—Moisture dependence of the bulk density of shelled yellow-dent field corn at 24° C.

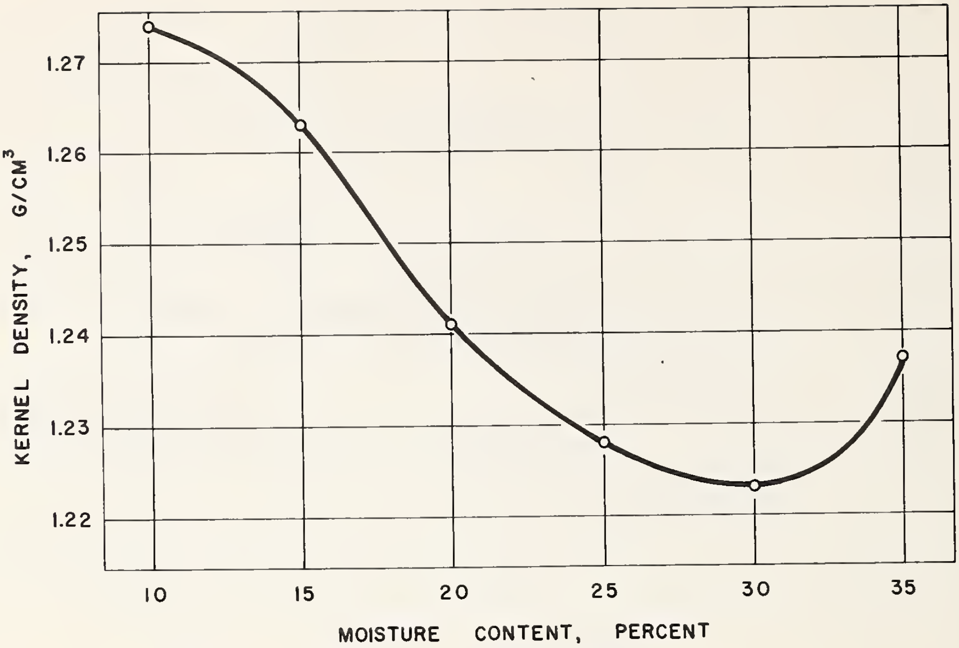


FIGURE 19.—Moisture dependence of the kernel density of shelled yellow-dent field corn at 24° C.

of the corn lots at 5-percent moisture-content intervals between 10 and 35 percent in the same way that values were obtained at these moisture levels for the dielectric properties. Mean values of the bulk density of the yellow-dent corn lots were calculated at each of these moisture levels, and the resulting relationship between moisture content and bulk density is shown in figure 18. The relationship between kernel density and moisture content for yellow-dent corn was obtained in a similar way (fig. 19). As observed earlier with hard red winter wheat (Nelson 1976), kernel density and bulk density are highly correlated up to about 25 percent moisture. Between 25 and 35 percent, bulk density of corn decreases continuously; however, the kernel density decreases between 25 and 30 percent and increases sharply between 30 and 35 percent moisture.

CONCLUSIONS

The 3-h oven-moisture method for shelled field corn samples, in which two-stage methods were employed above 13 percent moisture and in which ground samples are dried for 3 h at 130° C, gave higher moisture-content values than the 72-h method in which whole kernel samples are dried for 72 h at 103°C. In the moisture ranges from 10 to 20 percent and 35 to 40 percent, the 3-h method yielded moisture contents about 1 percentage point higher than the 72-h method. In the 20- to 35-percent-moisture range, differences between the two methods ranged from about ½ to 1 percent moisture.

Dielectric constants of corn samples at all three frequencies (20 MHz, 300 MHz, and 2.45 GHz) increased regularly with moisture content in the range from 10 to 35 percent. Mean values for shelled, yellow-dent field corn ranged from about 3.4 to 6.7 at 20 MHz, 2.8 to 5.2 at 300 MHz, and 2.4 to 4.9 at 2.45 GHz. The dielectric loss factor and the loss tangent and conductivity, which are both dependent upon the loss factor, are much less regular in their dependence on moisture content. The coefficients of variation, indicating the variability in dielectric properties among different lots of corn in particular moisture ranges, were also lower for the dielectric constant than they were for the dielectric loss factor.

The dielectric constant, ϵ_r', of shelled corn increases with the bulk density, ρ_b, of the grain. The relationship seems to be nearly linear. When a given corn sample is settled to different bulk densities, the slope of the ϵ_r'-versus-ρ_b line increases as the moisture content of the grain increases, indicating that the variation in dielectric constant attributable to changes in bulk density is enhanced by moisture.

The dielectric constant of shelled corn increases

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with temperature. The ϵ_r'-versus-temperature curves are nearly linear at low moisture levels, but the relationship seems to depart from linearity at high moisture contents, particularly at the 20-MHz frequency. Mean thermal coefficients for ϵ_r' between 25° and 60° C range from about 0.01/°C at 2.45 GHz for 10-percent-moisture corn to about 0.02/°C at 20 MHz for 19-percent-moisture corn. The magnitude of the thermal coefficient for ϵ_r' increases with moisture content and decreases with frequency in the ranges studied.

In general, the dielectric constant seems to be the most reliable of the dielectric properties to use for sensing moisture content of grain by high-frequency or microwave methods because of its regular behavior and lower variability among grain lots. These studies did not identify any advantage of one frequency over the other for those considered (20 MHz, 300 MHz, and 2.45 GHz), because the variation in dielectric constant observed was about the same at each frequency.

Dependence of the dielectric constant on sample bulk density and temperature must be taken into account for any accurate measurement of grain moisture content by electrical measurements that utilize the correlation of dielectric constant and moisture content. Some quantitative data concerning the dependence of the dielectric constant on these two variables were developed in these studies. There are two aspects of dependence on bulk density to be considered: one is the variation of bulk density for a given sample, and the other is the variation of bulk density among different grain lots. Only the first aspect is easily studied, because the influence of bulk density of different grain lots is confounded by other physical and chemical differences. Data reported here included considerable information on these other physical and chemical composition properties of all the corn lots studied, but the particular influence of these various other factors on the dielectric properties has not yet been determined.

Differences were noted between the dielectric properties of yellow-dent corn and the two lots of flint corn and the single floury-endosperm corn lot, but these differences can be accounted for by differences in bulk density.

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